

**Final Report Prepared 7/18/05 for the
National Aeronautics and Space Administration
on grant NCC3-796 entitled**

SURFACE COLLISIONS INVOLVING PARTICLES AND MOISTURE (SCIP'M)

by Professor Robert H. Davis
Department of Chemical and Biological Engineering
University of Colorado
Boulder, Colorado 80309-0424

ABSTRACT

Experiments were performed on the collision of a solid sphere with a nearly horizontal flat surface covered with a thin layer of viscous liquid. High-speed collisions were obtained by dropping the ball onto the surface from various heights, using gravitational acceleration. Low-speed collisions were obtained using pendulums with long strings or by launching the balls at low velocities in the reduced-gravity environment of parabolic flight. The sphere bounces only when the impact velocity exceeds a critical value. The coefficient of restitution (ratio of rebound velocity to impact velocity) increases with increasing impact velocity above the critical value, indicating the increasing relative importance of elastic deformation to viscous dissipation. The critical impact velocity increases, and the coefficient of restitution decreases, with increasing viscosity or thickness of the liquid layer and with decreasing density or size of the sphere. The ratio of the wet and dry coefficients is expressed as a function of the Stokes number (ratio of particle inertia and viscous forces), showing good agreement between theory and experiment.

Similar experiments were performed with the flat surface inclined at various angles to the approaching sphere. A modified Stokes number, which is a measure of the ratio of inertia of the sphere in the normal direction to the viscous forces exerted by the fluid layer, was used for the analysis of oblique collisions. Even for these oblique collisions, it was found that no rebound of the ball was observed below a certain critical Stokes number. The coefficient of normal restitution, defined as a ratio of normal rebound velocity to normal approach velocity, was found to increase beyond the critical Stokes number and even out as it approaches the value for dry restitution at high Stokes numbers. It was also found that, for smooth spheres like steel, the normal restitution at the same modified Stokes number is independent of the angle of impact. The tangential coefficient of restitution, defined as the ratio of tangential rebound velocity to tangential approach velocity, is found to be nearly unity, except for very low approach velocities. Thus, as a first approximation, the theories that predict the coefficient of restitution for head-on wet collisions can be extended to predict the coefficient of normal restitution for oblique wet collisions.

Additional experiments were performed with soft surfaces in which a porous cloth or sponge layer was placed over the hard, flat surface. In these experiments, the coefficient of restitution was found to decrease with increasing impact velocity, due to inelastic losses in the soft material. A model combining inelastic deformation and flow through porous media was developed to describe these findings.

INTRODUCTION AND OBJECTIVES

Particle collisions with other particles or with surfaces play key roles in granular and suspension flows, agglomeration and filtration processes, and the dynamics of planetary rings. When the surfaces are moist or wet, fluid-mechanic forces as well as solid-mechanic forces influence the outcome of each collision.

This report describes the results of the NASA-supported project, Surface Collisions Involving Particles and Moisture (SCIP'M), performed at the University of Colorado. The primary objective of this research was to gain a fundamental understanding of particle collisions with surfaces (or other particles) when both solid mechanics and fluid mechanics play important roles. The focus of experiments was on oblique collisions between a particle and a wet or moist surface. As shown by Davis *et al.* (1986), the collision of a particle with a flat surface provides results that may be generalized to those for the collision of two particles of arbitrary size ratio. The conditions for which the particle bounces or skips off the surface, rather than sticking to it, were determined. The relative roles of fluid and solid forces during the impact were assessed with the aid of theory. Specific questions for which answers were sought include

- ◆ *When will a particle stick to a wet surface instead of rebounding?*
- ◆ *For rebound, how are the receding angle and velocities related to the approaching angle and velocities?*
- ◆ *What forces and torques occur during a collision, and to what extent can they be described by classical lubrication, elastic, and friction theories?*

The above questions were answered through a combination of theory and experiment. The latter included both high-speed collisions under normal gravity and low-speed collisions in the reduced-gravity environment of parabolic flight. Reduced gravity is necessary for low-speed collisions, because normal gravitational acceleration otherwise would obscure the rebound behavior. The proposed research had three primary objectives or tasks:

- (i) **Ground-based experiments:** The initial experiments were performed in the PI's laboratory at the University of Colorado. The goals of these ground-based experiments were to develop and test the experimental design and to obtain data on high-speed collisions. Typical impact speeds for these experiments are on the order of 0.5-3 m/s, achieved by dropping small balls from heights of 1-50 cm above the surface.
- (ii) **Flight experiments:** Additional experiments were performed using the brief low-gravity environment afforded by parabolic flight. These experiments typically have smaller impact velocities on the order of 1-10 cm/s, although some experiments were performed with higher impact speeds to compare with the ground-based results. A pendulum setup was also employed for ground-based, low-velocity collisions.
- (iii) **Theory:** Supporting theory was developed to interpret the experimental findings. The elastohydrodynamic theory of head-on collisions of wet particles/surfaces, originally developed by Davis *et al.* (1986) was extended to account for oblique collisions and solid-contact forces. Together with the experimental results, the theory allows for determination of the relative contributions of liquid lubrication forces and solid elastic and friction forces during impact, and how they depend on physical parameters such as the liquid layer thickness and viscosity, the solid surface roughness, and the inertia of the impacting particle.

SIGNIFICANCE

This work provides new understanding of fluid-solid phenomena during collisions, particularly in the relatively unstudied cases of oblique collisions and wet surfaces. Of practical importance are new criteria for determining whether a particle will stick or rebound subsequent to colliding with a surface or another particle, and semi-empirical relations for predicting the rebound velocity, rotation, and angle from the approach trajectory and the solid and liquid properties. It is anticipated that the results of the proposed study will improve our understanding of a number of fields where collisional processes are important, including filtration, agglomeration, suspension flow, granular flow, pollen capture, pulmonary drug delivery, and perhaps even planetary rings. The results may also help with dust control and the handling of granular materials, such as would be important in human exploration of Mars.

ACCOMPLISHMENTS

Ground-based Collision Experiments

Ground-based experiments were initially performed in our laboratory using the apparatus shown in Figure 1. The spheres are made of teflon, nylon 66 or stainless steel, and the flat surface on which they were dropped is a quartz disk. The smooth quartz surface was overlaid with a thin layer of a viscosity-standard oil. The material properties are provided in Table 1. The thickness of the oil layer was calculated by measuring the difference in weight between the dry and wetted disk. Each sphere was dropped from an apparatus above the disk at an adjustable height by placing it in a hole and then releasing it by quickly moving down the finger which had held it in place. The motion of the sphere before and after impact was recorded with an Olympus OM-1 35 mm camera and General Radio Company type 1531-A stroboscope. The fluid layer only slowly flowed down the quartz surface when inclined. To minimize this effect, the disk was placed on a flat surface and rotated 180° about its axis between experiments. For oblique collisions at high angles, the disc was removed periodically and the oil was reapplied.

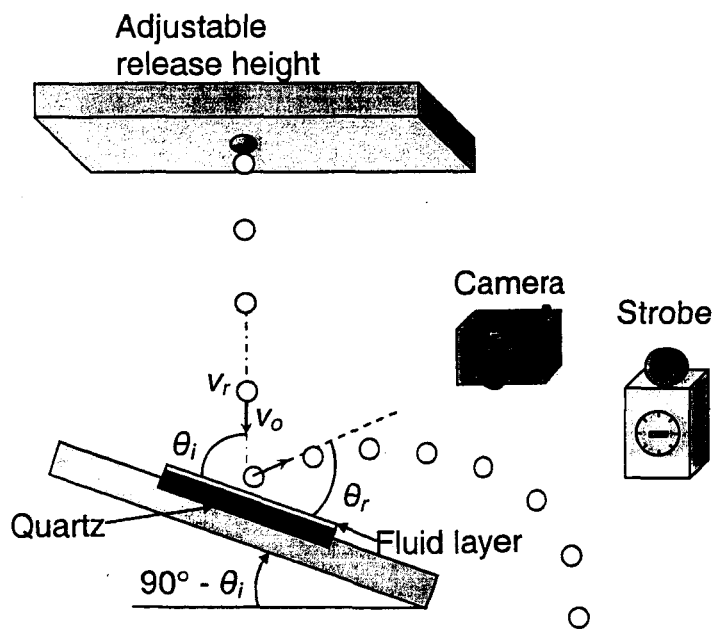


Figure 1 - Schematic of the experimental setup for ground-based laboratory experiments.

Table 1 – Properties of fluids and solids employed at 23°C

Material	Density (g/cm ³)	Viscosity (g/cm-s)	Young's Modulus (g/cm-s ²)	Poisson's Ratio (–)
Nylon 66	1.14	n/a	2.84×10^{10}	0.35
Steel 302	7.96	n/a	2.00×10^{11}	0.28
Quartz Disk	n/a	n/a	7.26×10^{11}	0.17
Fluid 1	0.972	9.9	n/a	n/a
Fluid 2	0.973	125	n/a	n/a

(i) Normal Collisions

The initial experiments were performed with the target nearly horizontal, so that the velocity of the ball was normal to the target surface (Davis *et al.*, 2002). Figure 2 shows typical stroboscopic photographs for the nylon ball with radius $a = 0.32$ mm dropped onto the quartz surface with and without a thin layer of the 9.9 P fluid with thickness $\delta = 80$ μ m. For the dry surface, the sphere rebounds with a velocity only slightly lower than the impact velocity. In contrast, no rebound is observed when the ball is dropped from height $h_o = 20$ cm onto the wetted surface. For $h_o = 30$ cm, rebound from the wet surface is observed, but the rebound velocity is much less than the impact velocity, due to viscous losses in the oil layer. Small ink dots were placed on the ball surface for some experiments, and these show a small rotation of approximately 2° between successive images on the photographs as the ball dropped, and a larger rotation of typically 5 - 10° between successive images during rebound.

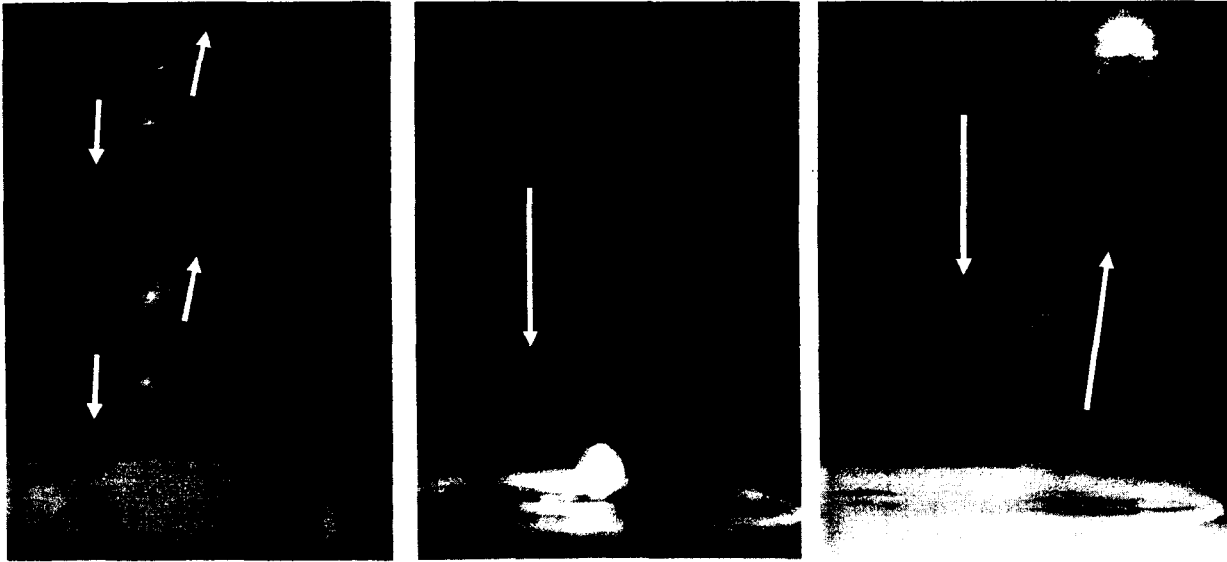


Figure 2: Strobed photographs of a nylon sphere of radius 0.32 cm dropped onto a dry quartz surface from a height of 20 cm (left panel), onto a quartz surface overlaid with a thin layer of fluid with 9.9 g/cm-s viscosity and 80 μ m thickness from a height of 20 cm (middle panel), and onto the quartz surface with the same fluid layer from a height of 30 cm (right panel).

Figure 3 shows that the rebound velocity is proportional to the impact velocity for dry collisions, over the range studied. The slopes of the lines give dry coefficients of restitution at the 90% confidence level of $e_{dry} = 0.88 \pm 0.04$, 0.86 ± 0.02 , and 0.84 ± 0.02 for nylon spheres of

radius 0.32, 0.48, and 0.64 cm, respectively, and $e_{dry} = 0.77 \pm 0.02$, 0.57 ± 0.05 , and 0.35 ± 0.05 , respectively, for steel spheres of the same sizes. The small losses for nylon are likely due to a combination of elastic waves, viscoelastic behavior, and vibrations of the thin quartz disk, whereas vibrations dominate the larger losses with steel balls.

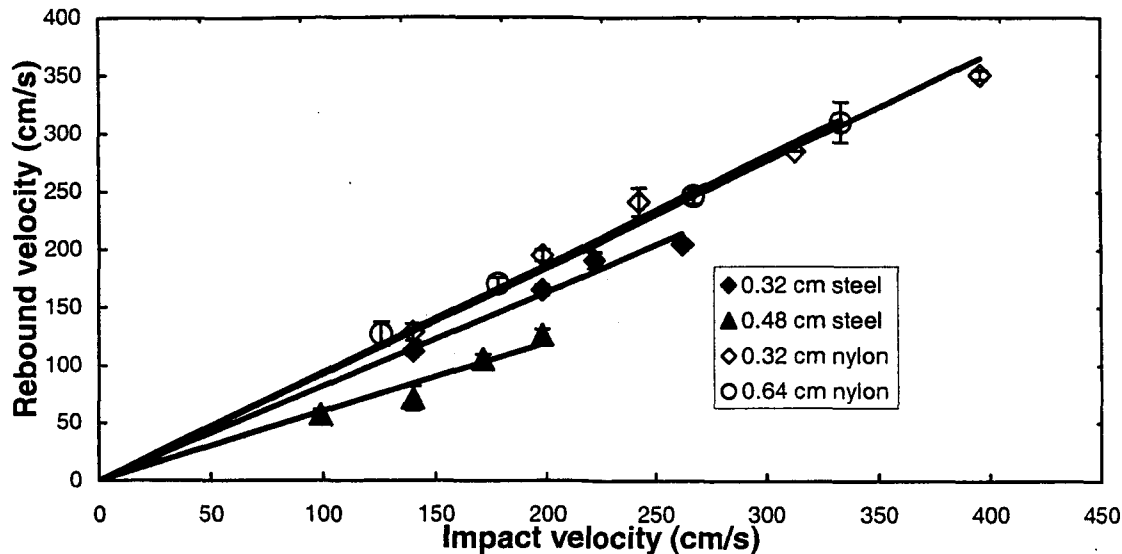


Figure 3: Linear increase of rebound velocity with impact velocity for normal collisions of nylon and steel spheres with a dry quartz disk of 0.64 cm thickness. The error bars represent plus and minus one standard deviation for typically 3-5 repeats for selected conditions.

Figure 4 for wet collisions shows a different behavior in that no rebound is observed until a critical impact velocity is reached, and then the rebound velocity increases rapidly at first and then almost linearly with impact velocity above the critical value. The critical impact velocity is higher for greater fluid thickness or viscosity (Figure 4a), due to increased viscous dissipation. On the other hand, the critical impact velocity is lower for a larger or more dense ball (Figure 4b), due to greater inertia which allows the ball to more easily penetrate the viscous layer and achieve elastic deformation.

The experimental results were analyzed by determining the apparent coefficient of restitution, defined as the ratio of the magnitudes of the rebound velocity and the impact velocity. Figure 5 shows a typical plot for a nylon ball of 0.32 cm radius dropped onto the quartz surface overlaid with fluid of different viscosities and thicknesses. Here, the coefficient of restitution is plotted versus the Stokes number defined by

$$St = \frac{mv_o}{6\pi\mu a^2} \quad , \quad (1)$$

where m is the mass of the sphere, v_o is the impact velocity, μ is the fluid viscosity, and a is the sphere radius. Below a critical Stokes number (corresponding to a critical impact velocity or drop height), the sphere does not bounce. With increasing Stokes number above the critical value, the coefficient of restitution increases due to the increase in the sphere's inertia relative to viscous forces (so that a greater fraction of the sphere's kinetic energy prior to impact is converted to elastic deformation rather than viscous dissipation). Additional results are reported by Davis *et al.* (2002).

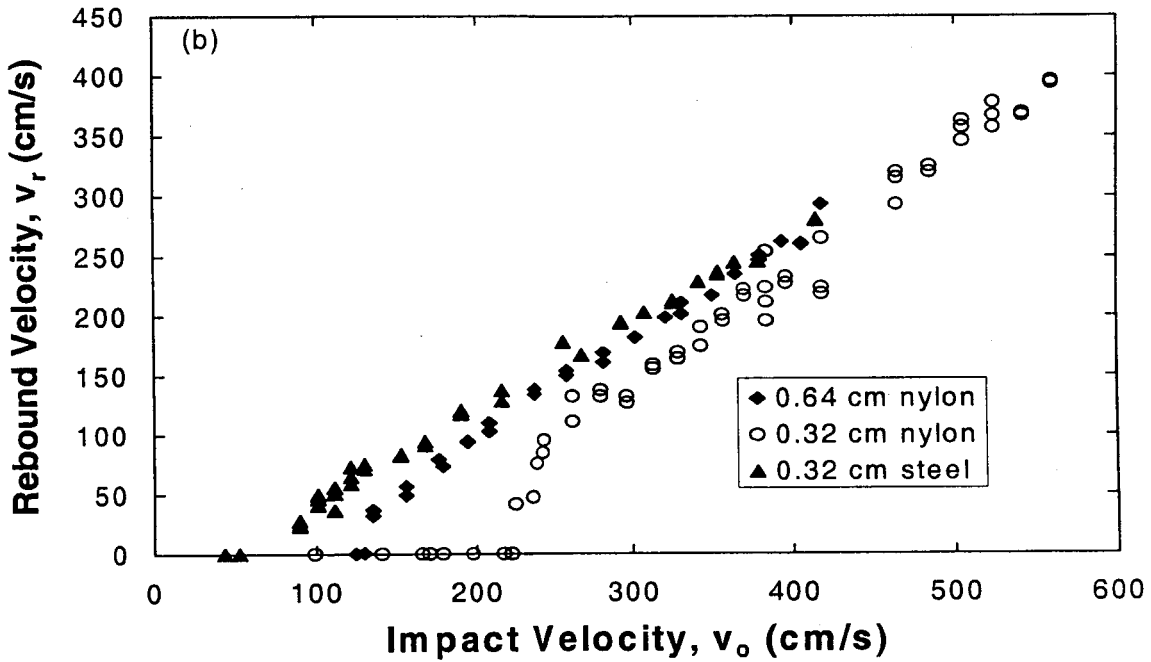
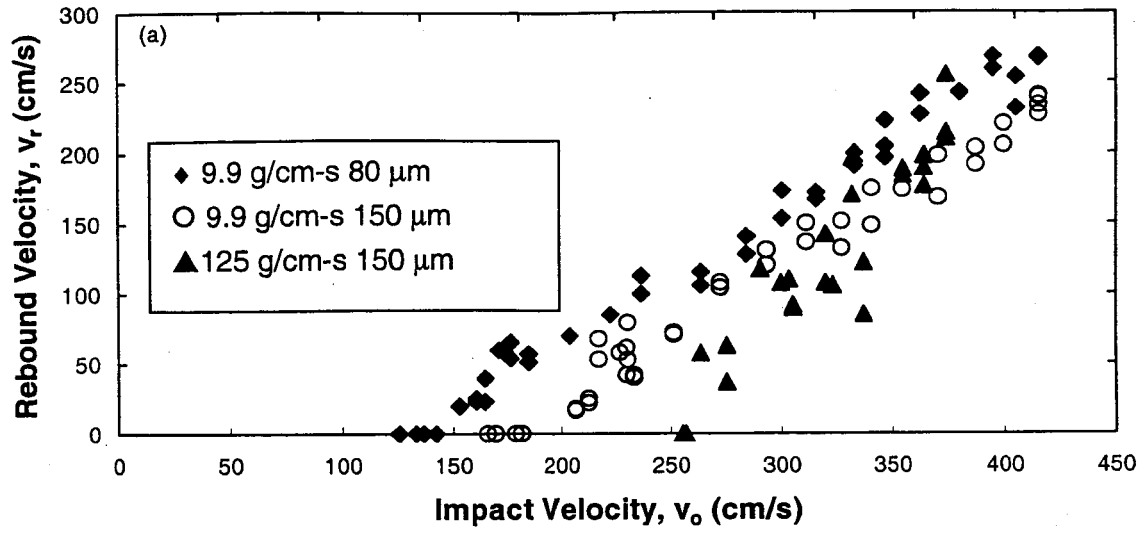


Figure 4: Increase in rebound velocity with impact velocity above a critical value for spheres dropped on a quartz disk overlaid with a thin viscous layer: (a) nylon spheres of 0.32 cm radius; (b) fluid of 125 g/cm-s viscosity and 80 μ m thickness.

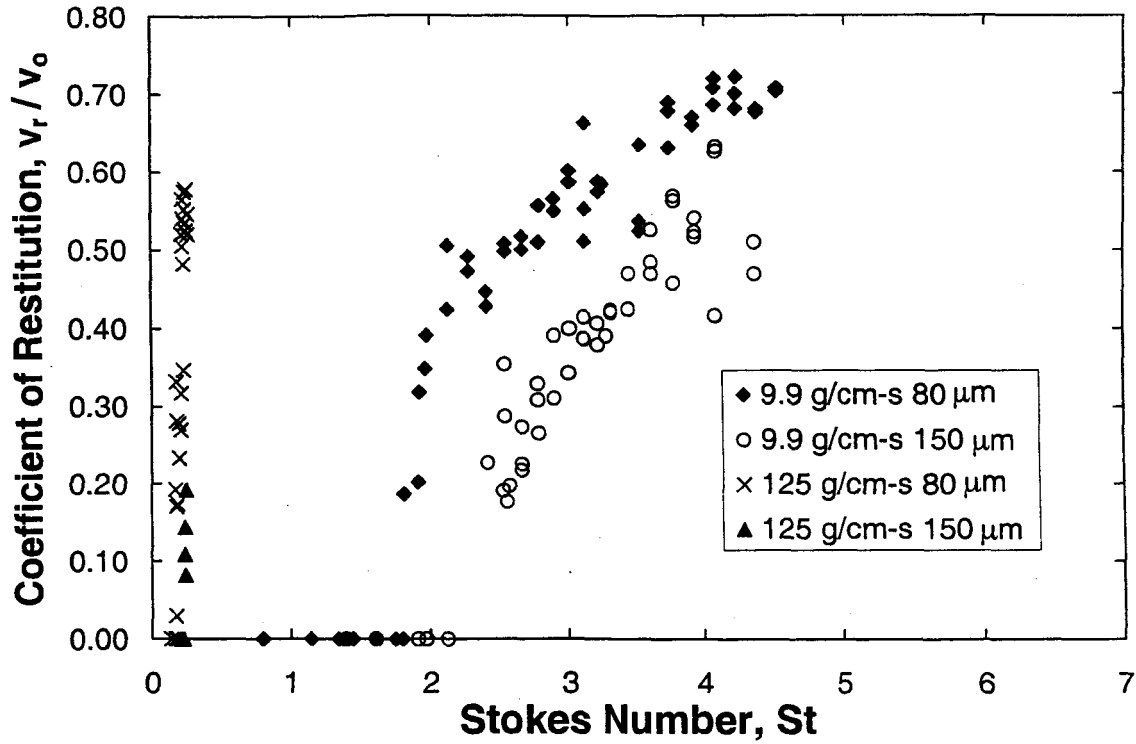


Figure 5: Coefficient of restitution versus Stokes number for nylon balls of radius 0.32 cm.

(ii) Oblique Collisions

Oblique impacts with dry and wet discs were examined for nylon, teflon and steel spheres (Kantak and Davis, 2004). Figure 6 provides plots of the normal rebound velocity versus the normal approach velocity for dry collisions of steel balls with a quartz disc, for various impact angles (θ_i , defined as the angle between the impact velocity and a tangent to the disk surface). It is seen that the data lie almost on a straight line. Linear regression was done to estimate the coefficient of normal restitution, e_{dry} (ratio of the normal component of the rebound velocity to the normal component of the approach velocity). The coefficients of dry restitution with $\pm 95\%$ confidence intervals are $e_{dry} = 0.90 \pm 0.01$, 0.82 ± 0.02 , 0.84 ± 0.04 for stainless steel balls of 0.64 cm diameter at $\theta_i \approx 87^\circ$, 45° , 30° , respectively. Stainless steel balls of 0.95 cm diameter gave $e_{dry} = 0.81 \pm 0.02$, 0.76 ± 0.02 , 0.75 ± 0.03 for $\theta_i \approx 87^\circ$, 45° , 30° , respectively. Nylon balls of 0.64 cm diameter gave $e_{dry} = 0.88 \pm 0.01$, 0.81 ± 0.02 , 0.81 ± 0.02 for $\theta_i \approx 87^\circ$, 45° , 30° , respectively. Nylon balls of 1.27 cm diameter gave $e_{dry} = 0.90 \pm 0.02$, 0.82 ± 0.03 , 0.81 ± 0.02 for $\theta_i \approx 87^\circ$, 45° , 30° , respectively. Teflon balls of 0.64 cm diameter gave $e_{dry} = 0.72 \pm 0.02$, 0.70 ± 0.02 , 0.72 ± 0.02 for $\theta_i \approx 87^\circ$, 45° , 30° , respectively. The losses in nylon and teflon spheres are probably due to the combined effect of elastic waves, viscoelasticity effects and vibrations in the disc. Vibrations are thought to be the major cause of losses for the dense steel spheres.

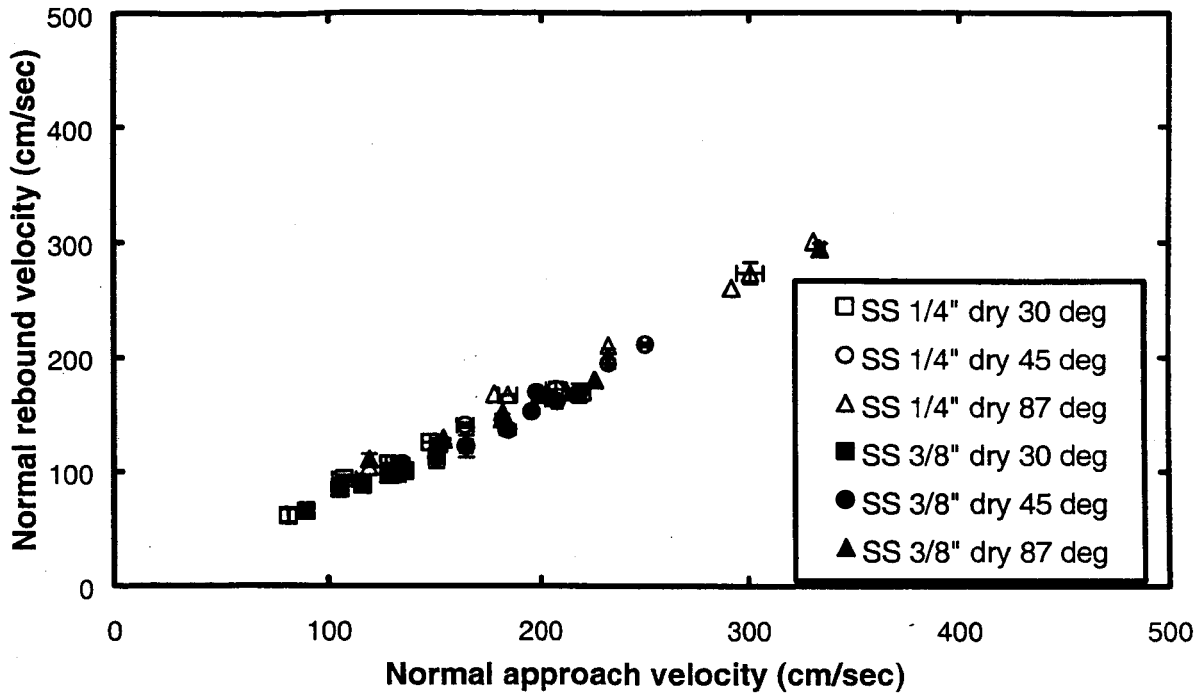


Figure 6: Normal approach velocity versus normal rebound velocity for impact with the dry quartz disc inclined at impact angles of 30°, 45° and 87° of stainless steel spheres of diameters 0.64 cm and 0.95 cm.

Figure 7 has plots of the tangential component of the rebound velocity versus the tangential component of the approach velocity for dry collisions. It is seen that all the data lie near the line with slope unity. Thus, there is not a significant reduction in velocity in the tangential direction, which implies that Coulombic friction for the materials and velocities investigated does not have a significant effect.

Figure 8 provides a plot of the normal rebound velocity versus the approach velocity for steel spheres impacting a quartz disc covered with a thin oil layer and inclined at three different angles. It is observed that, as the impact angle increases for the same impact velocity, the normal rebound velocity increases. This behavior is expected because, as the impact angle is increased toward normal, the normal component of velocity of the approaching sphere increases. A greater normal approach velocity leads to a greater rebound in the direction normal to the disc. Also, the critical impact velocity for rebound is lower for smaller viscosity due to less viscous dissipation.

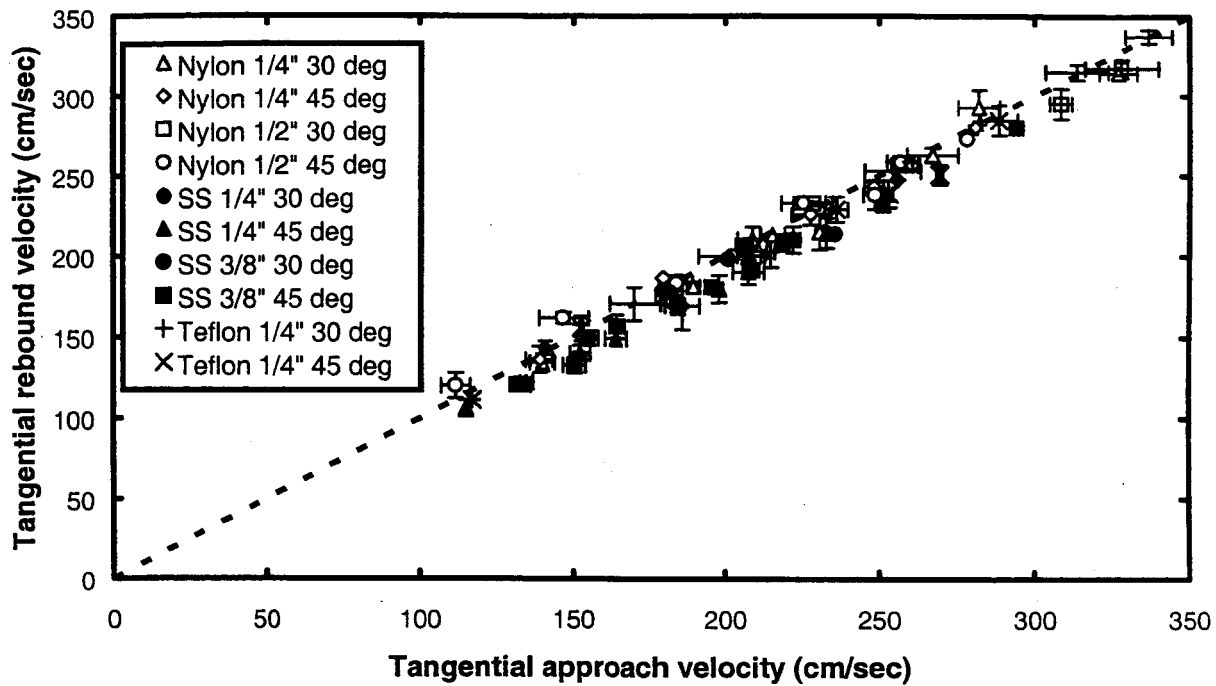


Figure 7: Tangential approach velocity versus tangential rebound velocity for nylon and steel spheres impacting the dry quartz disc at angles of 30° and 45°. The dashed line has slope unity.

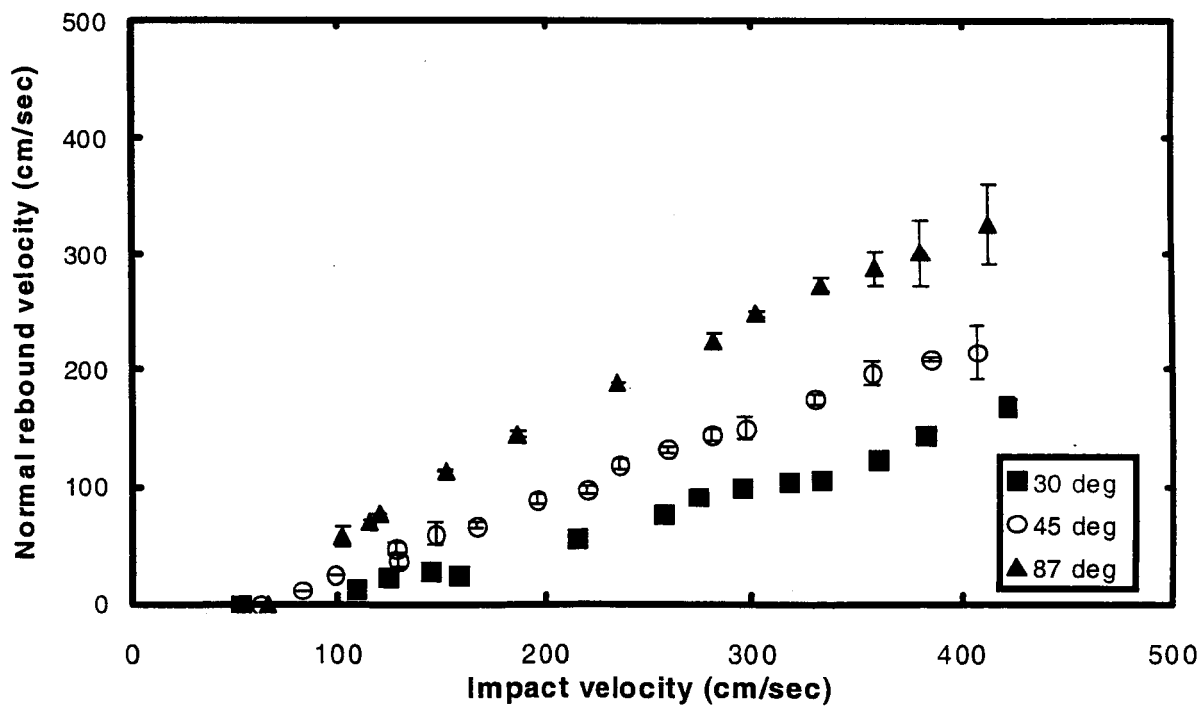


Figure 8: Normal rebound velocity versus normal approach velocity for stainless steel spheres of 0.64 cm diameter impacting the quartz disc covered with an oil layer of thickness 80 microns and viscosity 9.75 g/cm-s.

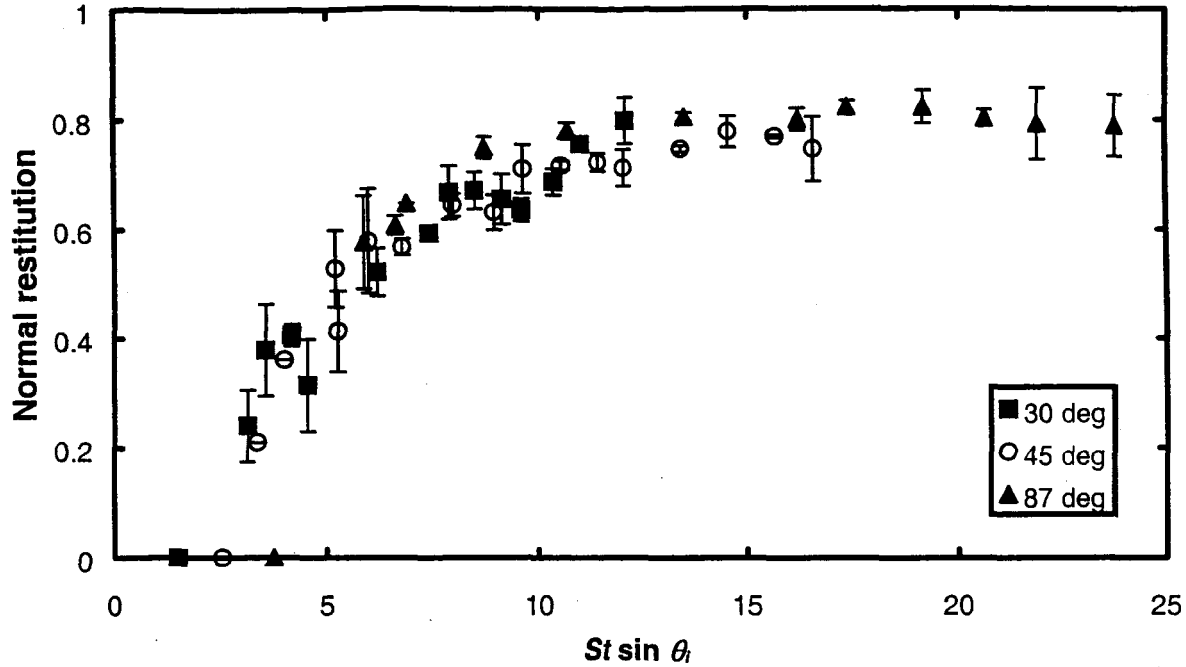


Figure 9: Coefficient of normal restitution versus the modified Stokes number for stainless steel spheres of 0.64 cm diameter impacting the quartz disc covered with an oil layer of thickness 80 microns and viscosity 9.75 g/cm-s.

Figure 9 is a plot of the wet coefficient of normal restitution (e_n) versus the modified Stokes number. The trends are the same as those observed in near-normal collisions (Davis *et al.*, 2002), i.e., e_n is zero for $St \leq St_c$ and increases for $St > St_c$ and approaches an asymptotic value for $St \gg St_c$. The critical Stokes number for rebound is smaller for the more viscous oil, as predicted by Davis *et al.* (1986), due to a larger elasticity parameter. More important, the data for various impact angles in Figure 9 appear to collapse on the same curve, except that the restitution for wet head-on collisions is slightly greater, as was also observed for dry collisions of the steel balls. This trend implies that the normal restitution of a stainless steel sphere depends only on the normal component of the impact velocity of the sphere and is independent of the impact angle. It further suggests that the normal and tangential components of velocity are decoupled. Thus, the theories that predict the coefficient of restitution for head-on wet collisions can be extended to predict the coefficient of normal restitution for oblique wet collisions. However, it was observed for rough spheres like nylon and teflon that the data do not collapse onto a single curve like that for steel spheres. The plastic spheres have much higher surface roughness than the steel spheres, and the roughness elements may have affected the collision and rebound process. Figure 10 is a plot of the coefficient of normal restitution versus the modified Stokes number for teflon spheres colliding with the wetted quartz disc at various angles.

In Figure 11, the coefficient of tangential restitution given by e_t (ratio of the tangential component of the rebound velocity to the tangential component of the approach velocity) is plotted versus the modified Stokes number for stainless steel spheres colliding with a wetted quartz disc. The values of e_t are close to unity, except for the most viscous oil at small Stokes numbers. Thus, the lubrication forces exerted by the oil layer do not significantly reduce the tangential component of the impact velocity, though they do impart a small rotation to the sphere (Kantak and Davis, 2004). Similar results were observed for the plastic spheres.

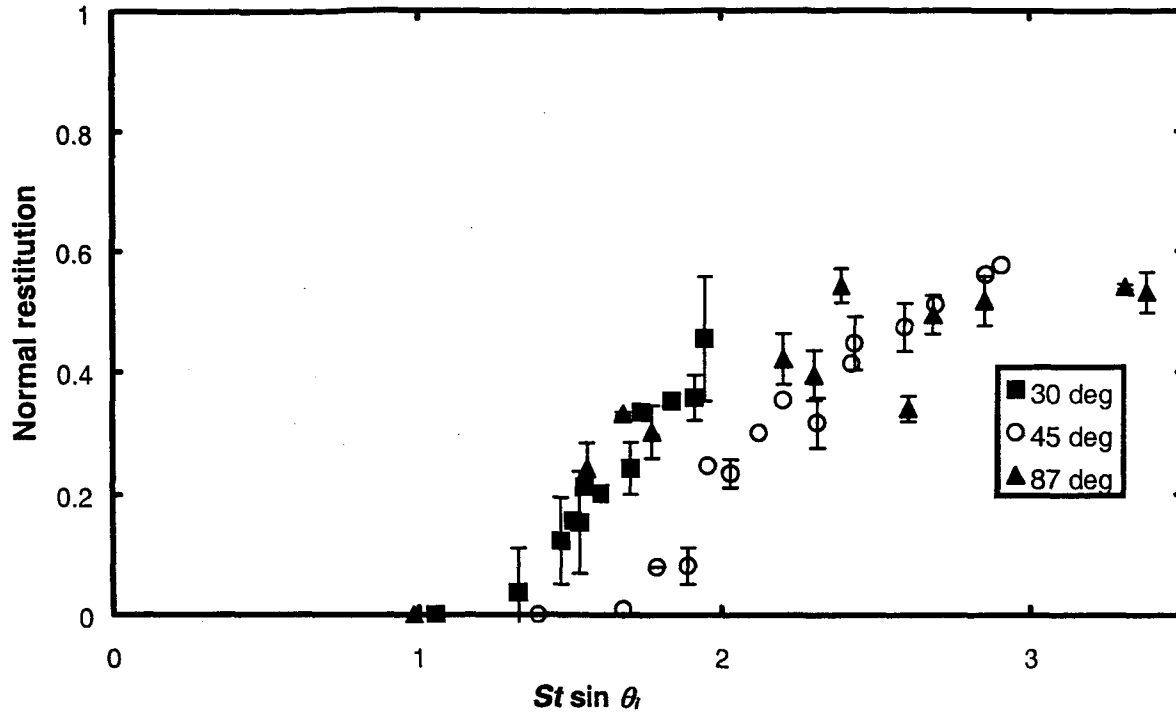


Figure 10: Coefficient of normal restitution versus the modified Stokes number for impact with a quartz disc covered with an oil layer of thickness 80 microns and viscosity 9.75 g/cm-s using teflon spheres of 1.27 cm diameter.

Theory for Head-on and Oblique Collisions

The theory for head-on collisions was extended from that developed previously by Davis *et al.* (1986). They showed that the coefficient of restitution is an increasing function of the Stokes number, representing the ratio of inertia and viscous forces, showing similar behavior to that exhibited in Figure 5. It also depends weakly on a dimensionless elasticity parameter, representing the ratio of viscous and elastic forces. As described by Davis *et al.* (2002), the coefficient of restitution for wet collisions is

$$e_{wet} = 0 \quad , \quad St \leq St_c \quad , \quad (2a)$$

$$e_{wet} = e_{dry} (1 - St_c/St) \quad , \quad St > St_c \quad , \quad (2b)$$

where St_c is the critical Stokes number required for rebound. From scaling arguments,

$$St_c \approx \frac{2}{5} \ln \left(\frac{4\sqrt{2}}{3\pi\epsilon} \right) \quad , \quad (3)$$

where ϵ is the dimensionless elasticity parameter defined by Davis *et al.* (1986). A more refined theory has recently been developed by Kantak and Davis (2005a), accounting for entrance effects as the sphere penetrates the thin liquid layer. A master plot of the experimental results for head-on collisions is provided in Figure 12. Good agreement with theory is obtained, though with considerable scatter in the data.

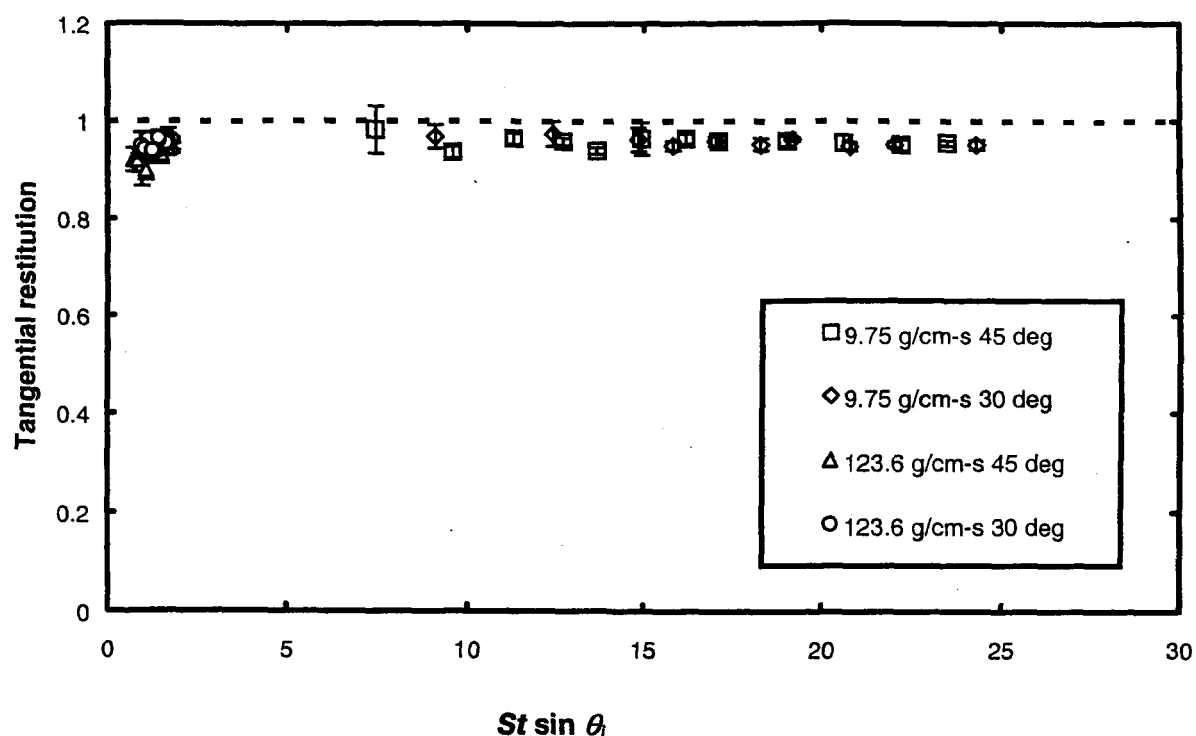


Figure 11: Coefficient of tangential restitution versus the modified Stokes number for stainless steel spheres of 0.64 cm diameter impacting an 80 microns thick oil layer of 9.75 or 123.6 g/cm-s viscosity.

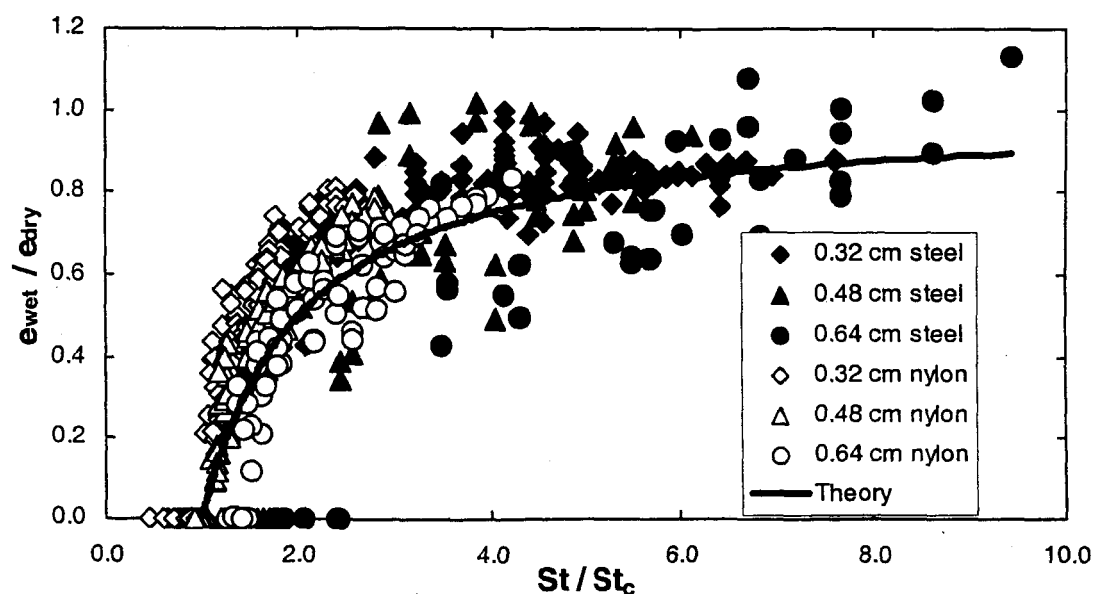


Figure 12: Coefficient of restitution for head-on wet collisions, normalized by that for dry collisions, versus the ratio of the Stokes number to its critical value (determined from Eq. (3)) for nylon (open symbols) and steel (closed symbols) balls impacting a quartz surface overlaid with an 80-250 μm layer of fluid with 9.9 g/cm-s viscosity. The theoretical curve is from Eq. (2).

For the oblique collisions, it is proposed, as a first approximation, that the normal and tangential components of the collisions are decoupled. Then, the above theory for head-on collisions may be applied to describe the normal component of oblique collisions. Equations (2a), (2b) and (3) still hold, but V_o, ε, St and St_c should be replaced by $V_o \sin \theta_i, \varepsilon \sin \theta_i, St \sin \theta_i$ and $St_c \sin \theta_i$, respectively. A scaling theory for the tangential lubrication stresses during an oblique collision is described by Kantak and Davis (2004). These stresses give rise to a slight reduction in the tangential velocity of the sphere and cause rotation of the sphere, with both effects becoming stronger as the Stokes number becomes small.

In Figure 13, the coefficient of normal restitution normalized by e_{dry} is plotted versus the ratio St/St_c for oblique collisions. As the theoretical predictions for the critical Stokes number are significantly different from the experimental value in many cases, the experimental values of St_c are used for this figure. Both theory and experiment show that the normal coefficient of restitution is zero for $St < St_c$ and then increases rapidly for $St > St_c$ before approaching e_{dry} asymptotically for $St \gg St_c$. The scatter in the data may be due, at least in part, to variable roughness on the surface of the spheres and nonuniformities in the oil-layer thickness. The tangential restitution and the sphere rotation also show good agreement between theory and experiment (Kantak and Davis, 2004).

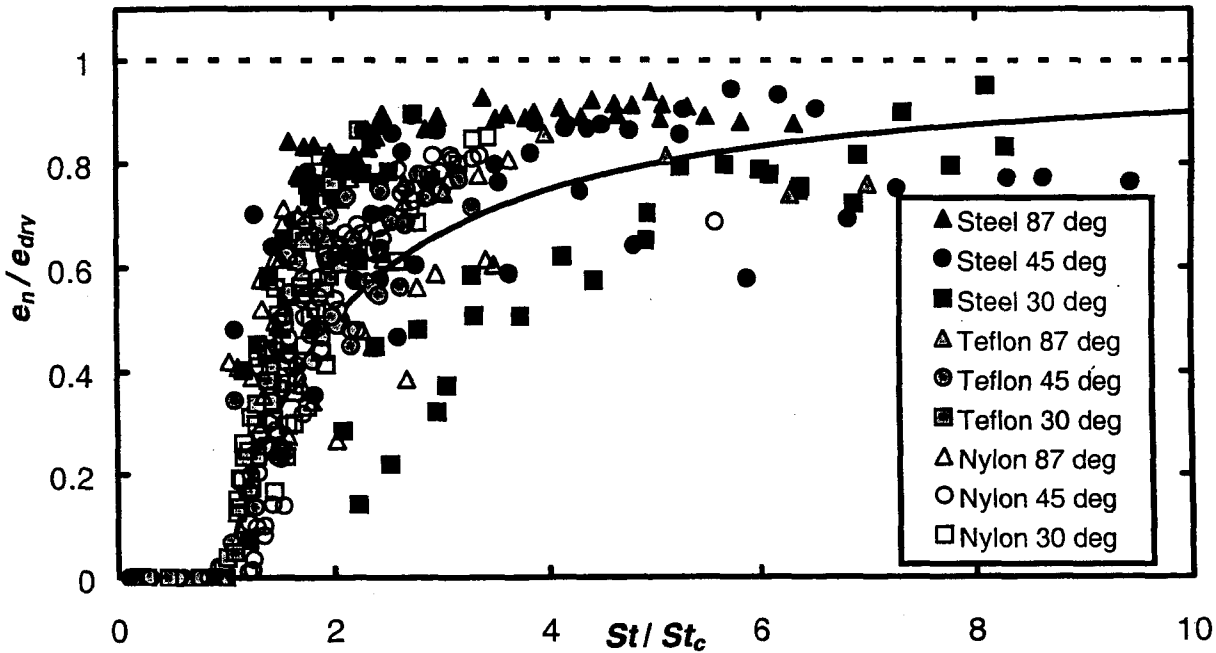


Figure 13: Normalized coefficient of normal restitution versus normalized Stokes number for stainless steel, teflon and nylon balls of various sizes impacting a quartz disc covered with an oil layer of thickness 80 microns and viscosity 9.75, 49.8 and 123.6 g/cm-s for various impact angles. The solid line is the theory from Eq. (2).

Theory and Experiments for Tangential Motion of a Sphere on a Rough Surface

Additional theoretical and experimental efforts focused on the tangential motion of a sphere moving down an inclined plane due to gravity in the presence of a viscous fluid. We have shown that a combination of gravitational, fluid-mechanic, and solid-mechanic forces govern the motion of the sphere and that physical contact occurs due to microscopic surface roughness (Galvin *et*

al., 2001). Roughness heights were determined by inverting the inclined surface and measuring the time required for the sphere to fall a specified distance. The solid contact forces include a normal component to balance the normal component of gravity, and a tangential component described by sliding or rolling friction. The experiments show that the sphere undergoes a combination of rolling and slipping when the inclination of the plane exceeds a critical angle. More recent work has shown that the sphere undergoes an erratic motion due to multiple roughness scales (Zhao *et al.*, 2002, Davis *et al.*, 2003).

Low-speed Collisions

Two campaigns of experiments with low-speed impacts were performed in July and October 2003, using reduced gravity during parabolic flight with KC-135 aircraft. Low gravity was required so that gravitational acceleration would not cause balls launched at low-speed to miss the target (indeed, even during the 'free-fall' phase of the flight, some balls missed the target due to residual accelerations). The KC-135 parabolic flight experiments were performed with the SCIP'M apparatus shown in Figure 14. It was constructed in the machine and electronics shop in the Department of Chemical and Biological Engineering at the University of Colorado, and uses a motor-controlled assembly to launch a set of balls at a pre-controlled velocity toward a quartz plate that is either dry or overlaid with a thin oil layer. Additional experiments with low-speed impacts were performed under gravity using pendulums with long strings. The results are described by Kantak *et al.* (2005).

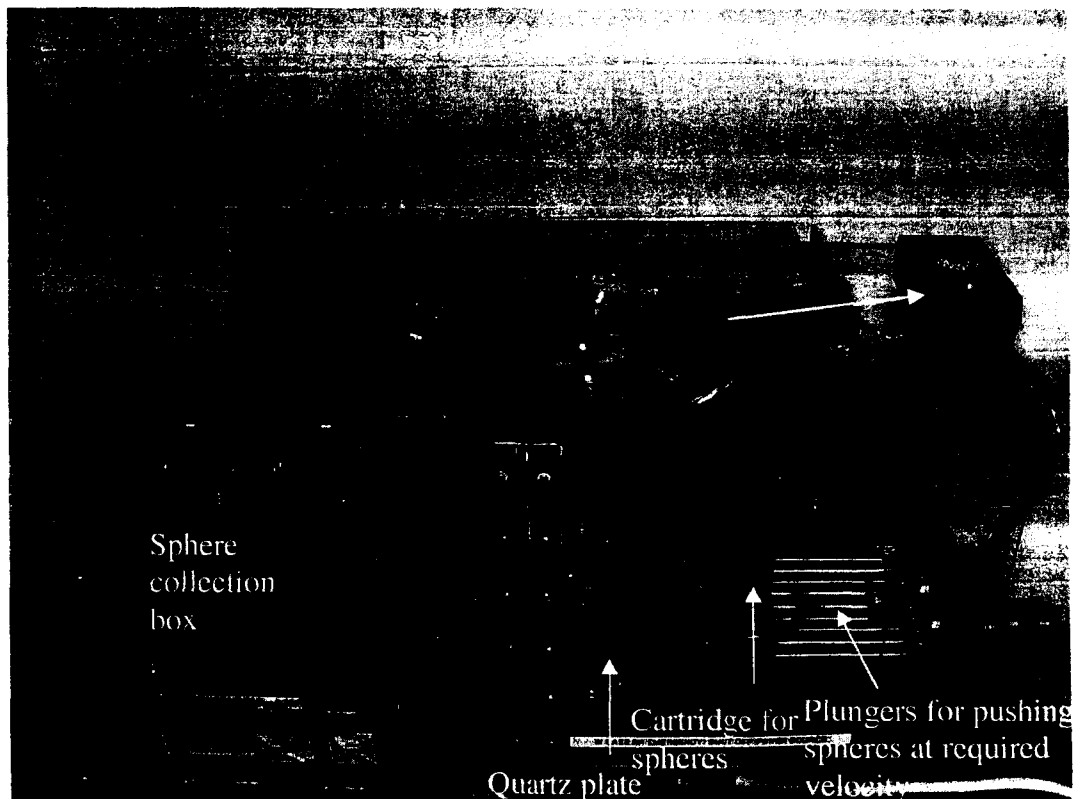


Figure 14. Photo of the Surface Collisions in Presence of Moisture (SCIP'M) device used for performing low-velocity collisions in the low-gravity parabolic flights of a KC-135 aircraft.

Figure 15 provides example results for a stainless-steel ball impacting a quartz disk overlaid with a thin layer of oil with 0.50 g/cm-s viscosity and 30 μm initial thickness. These results show a critical impact velocity, below which no rebound occurred, and then an increasing coefficient of restitution with increasing impact velocity above the critical value, similar to the results for high-speed collisions involving much more viscous oils. Indeed, both the low-velocity and the high-velocity results collapse on a single curve, described by Eq. (2), when properly nondimensionalized (see Figure 16). The low-gravity (flight) and pendulum experiments are in good agreement. This finding is especially important, as the low-gravity experiments are expensive and difficult (especially at very low velocities, where residual accelerations cause the ball to miss the target).

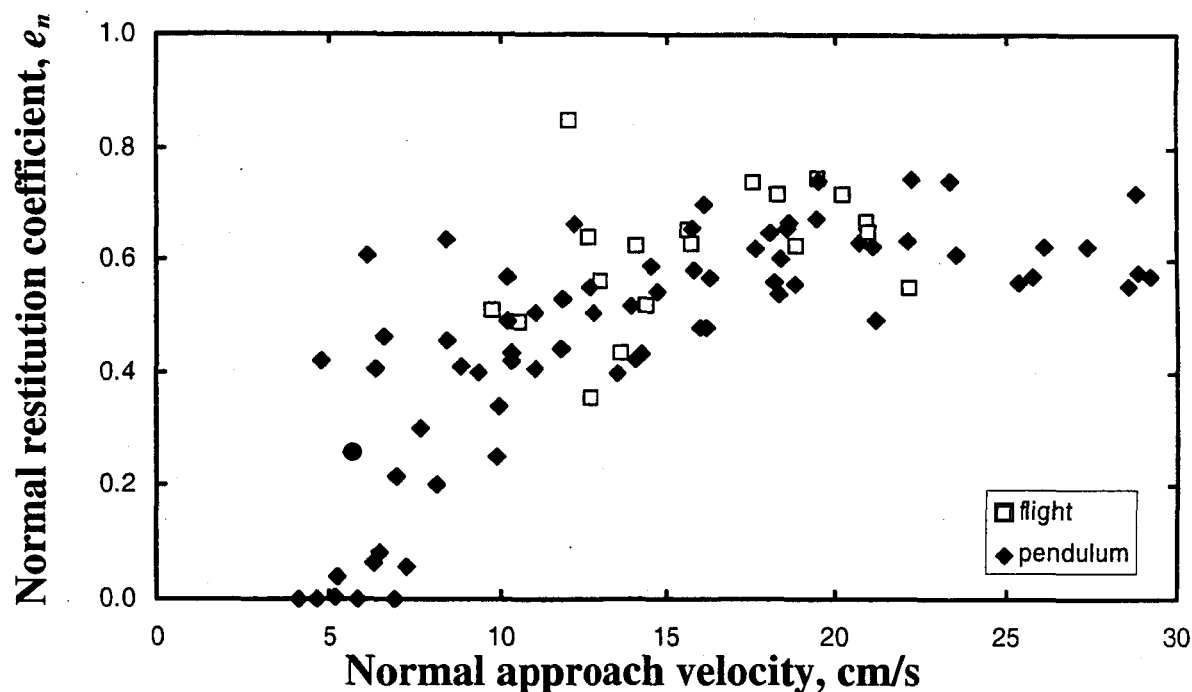


Figure 15. Coefficient of normal restitution versus normal approach velocity for near-normal impact of a stainless-steel sphere of 0.64 cm diameter with a quartz plate covered with an oil layer of viscosity 0.50 g/cm-s and initial thickness of 30 μm .

Soft Collisions

Additional experiments were performed, using both low gravity (SCIP'M apparatus) and normal gravity (pendulum), when the quartz surface was covered with a thin, porous cloth or sponge that was either dry or wetted with water. These materials have inelastic properties and provide for soft collisions that experience additional losses over the hard collisions described earlier. An example of the results of both experiment and theory are shown in Figure 17 for near-normal collisions. The dry coefficient of restitution is approximately 0.6 and declines with increasing impact velocity, due to the inelastic losses in the thin fabric. The wet coefficient of restitution is even lower, due to additional viscous losses. Moreover, in contrast to the results in the absence of a soft, porous layer, the wet coefficient of restitution decreases with increasing impact velocity and there is no critical impact velocity below which no rebound is seen. Additional results are reported in Kantak and Davis (2005b).

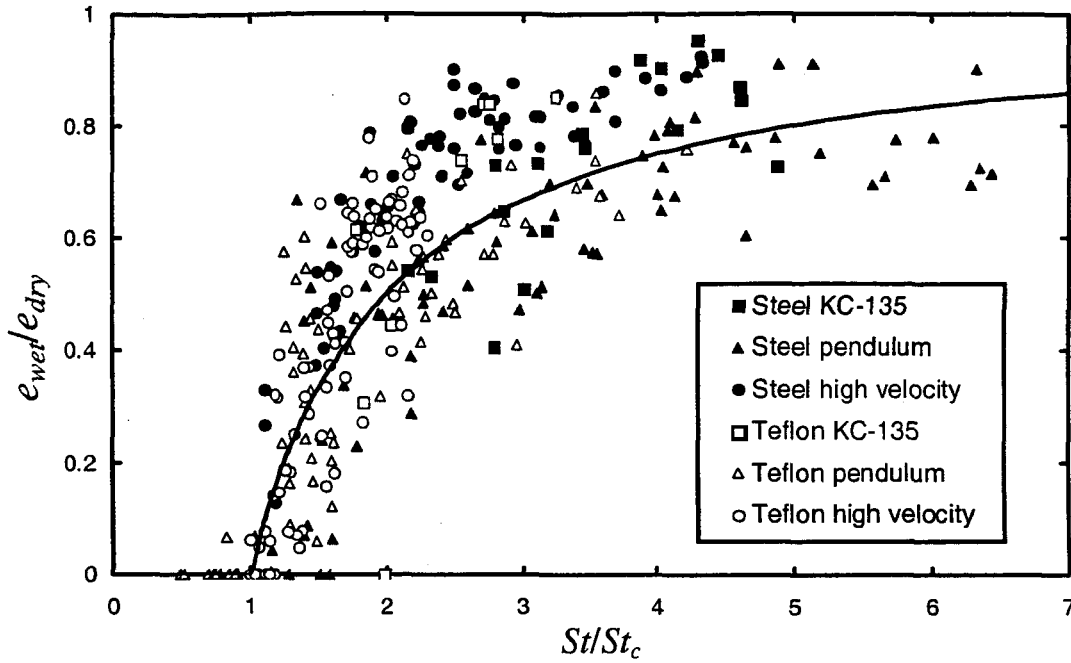


Figure 16. Wet restitution coefficient normalized by the dry restitution coefficient versus the ratio of Stokes number and critical Stokes number for collisions with a 0.127 cm thick quartz target. Data from the low-velocity flight and pendulum experiments are for 0.64 cm stainless steel spheres and 0.95 cm Teflon spheres and an oil layer of viscosity 0.5 g/cm-s and initial thickness of 30 microns. Data from the high-velocity, ball-dropping experiments are for 0.64 cm stainless steel spheres and a 150 microns thick oil layer of viscosity 9.75 g/cm-s, and 0.64 cm Teflon spheres and a 80 microns thick oil layer of viscosity 124 g/cm-s. The solid line is the theoretical curve given by Eq. (2).

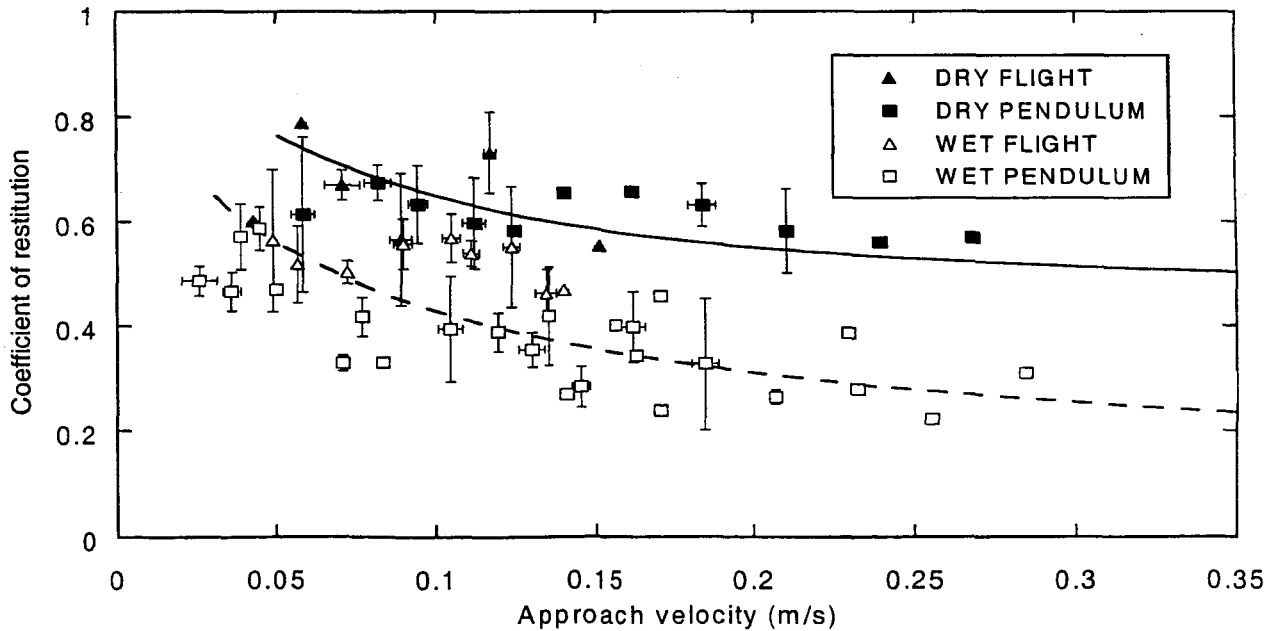


Figure 17. Restitution coefficient versus approach velocity data for 0.64 cm Teflon spheres impacting a dry or wet layer of thin cloth placed on a 1.27 cm thick quartz plate in low-gravity KC-135 flights and pendulum experiments under normal gravity. The fabric was wetted by saturating it with water. The solid and dashed curves represent the theory for the dry and wet collisions, respectively.

PERSONNEL

The research has primarily been undertaken by Professor Robert H. Davis, Graduate Research Assistants Janine Galvin, Brian Good and Advait Kantak, and Undergraduate Research Assistants Dean Rager and Doug Wildemuth. Another Graduate Research Assistant, Yu Zhao, assisted with the theory and experiments on the tangential motion of a sphere down an inclined plane. This latter work has been undertaken in collaboration with Professor Kevin Galvin at the University of Newcastle. Finally Research Associate, Mike Rother, assisted with the project.

REFERENCES

- Davis, R. H., J.-M. Serayssol, and E. J. Hinch, "The Elastohydrodynamic Collision of Two Spheres," *J. Fluid Mech.* **163**, 479-492 (1986).
- *Galvin, K. P., Y. Zhao, and R. H. Davis, "Time-averaged Hydrodynamic Roughness of a Noncolloidal Sphere in Low Reynolds Number Motion Down an Inclined Plane," *Phys. Fluids* **13**, 3108-3120 (2001).
- *Davis, R. H., D. A. Rager, and B. T. Good, "Elastohydrodynamic Rebound of Spheres from Coated Surfaces," *J. Fluid Mech.*, **468**, 107-119 (2002).
- *Davis, R. H. Y. Zhao, K. Galvin, and H. Wilson, "Solid-solid Contacts Due to Surface Roughness and Their Effects on Suspension Behavior," *Phil. Trans. R. Soc. London* **361**, 871-894 (2003).
- *Zhao, Y., K. P. Galvin, and R. H. Davis, "Motion of a Sphere Down a Rough Plane in a Viscous Fluid," *I. J. Multiphase Flow*, **28**, 1787-1800 (2002).
- *Kantak, A. A. and R. H. Davis, "Oblique Collisions and Rebound of Spheres from a Wetted Surface", *J. Fluid Mech.* **509**, 63-81 (2004).
- *Kantak, A. A. and R. H. Davis, "Elastohydrodynamic Theory for Wet Oblique Collisions," *Powder Tech.* (2005a, under review).
- *Kantak, A. A. and R. H. Davis, "Collisions of Spheres with Wet and Dry Porous Layers on a Solid Wall," *Chem. Eng. Sci.* (2005b, under review).
- * Kantak, A. A., J. E. Galvin, D. J. Wildemuth, and R. H. Davis, "Low-velocity Collisions of Particles with a Dry or Wet Wall," *Microgravity Sci. & Tech.* **XVII-1**, 18-25 (2005).
- *work supported by NASA grant NCC3-796.